Characterization of an Embedded RF-MEMS Switch

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***Abstract* — An RF-MEMS capacitive switch for mm-wave integrated circuits, embedded in the BEOL of 0.25µm BiCMOS process, has been characterized. First, a mechanical model based on Finite-Element-Method (FEM) was developed by taking the residual stress of the thin film membrane into account. The pull-in voltage and the capacitance values obtained with the mechanical model agree very well with the measured values. Moreover, S-parameters were extracted using Electromagnetic (EM) solver. The data observed in this way also agree well with the experimental ones measured up to 110GHz. The developed RF model was applied to a transmit/receive (T/R) antenna switch design. The results proved the feasibility of using the FEM model in circuit simulations for the development of RF-MEMS switch embedded, single-chip multi-band RF ICs.**

***Index Terms* — FEM analysis, Embedded MEMS, RF-MEMS switch, mm-wave circuits, monolithic integration**

I. INTRODUCTION

During last decade, silicon-based technologies have become more attractive for RF applications due to the emergence of the Silicon-Germanium (SiGe) technology. The integration of discrete RF components of a transceiver into a single chip has become feasible, leading to cost and area effective solutions for the communication market. Various micromachining technologies developed for microelectromechanical systems (MEMS) have been spotlighted in the field of RFICs as promising technological option to achieve improvement in size, cost and performance [1-3].

The latest developments in RF-MEMS technology have paved the way for achieving high performance and IC-integrated MEM devices/systems, especially RF-MEMS switches. RF-MEMS switches are one of the key components for the development of the next generation multi-band communication circuits/systems [4, 5]. Low insertion-loss, high-isolation, high linearity, near zero DC power consumption and low cost of RF-MEMS switches are the most attractive features for RF circuit designers. In the literature, standalone RF-MEMS switches were successfully demonstrated [6], and several methods were also suggested for integrating them into IC processes [7-10]. Among these methods, integration of MEMS switches into a standard CMOS or BiCMOS Back-end-of-Line (BEOL) is appearing to be the most promising one to enable the realization of fully integrated multi-band transceivers [11].

FEM (Finite-Element-Method) analysis is the common method for behavioral analysis of MEMS structures. Mechanical behavioral analyses are important. For instance, the electrical performance of the RF circuits is determined by the mechanical behavioral of RF-MEMS switch. RF circuit designers need simple and accurate behavioral models of embedded RF switches in CAD tools to enable system-level simulations.

In this work, a capacitive-type MEMS switch was designed using CoventorWare® to analyze the mechanical characteristics. The pull-in voltage and the extracted capacitance values of the switch from CoventorWare® simulations are similar to the measurement results unless by taking the initial stress of the thin film into consideration. High frequency performance was simulated using Agilent® MOMENTUM EM solver for two different mechanical states. The contact region was modeled as RLC circuit. The RF performance of the switch was characterized up to 110GHz and compared with the measured S-parameters. Both the mechanical and the RF simulations are very similar to the measurement results. The developed RF model was successfully applied to a T/R antenna switch design. The results proved the feasibility of using the FEM models in circuit simulations for the development of RF-MEMS switch integrated, single-chip multi-band RF ICs.

II. TECHNOLOGY

The fully embedded RF-MEMS switch was built between the Metal2 (M2) and Metal3 (M3) of BEOL metallization of IHP's 0.25µm BiCMOS process (Fig. 1) [12]. The thin TiN cap layer, which is a part of the BiCMOS MIM capacitor, forms the contact region of the switch. High-voltage electrodes were formed using Metal1 (M1) while M2 was used as RF signal line. The membrane was realized using the stress compensated Ti/TiN/AlCu/Ti/TiN M3 stack. The standard BiCMOS process was completed with only an additional 1-mask process that includes wet-etching of BEOL SiO_2 and critical-point drying on 8-inch wafers. A micrograph of the fabricated switch is shown in Fig. 2.

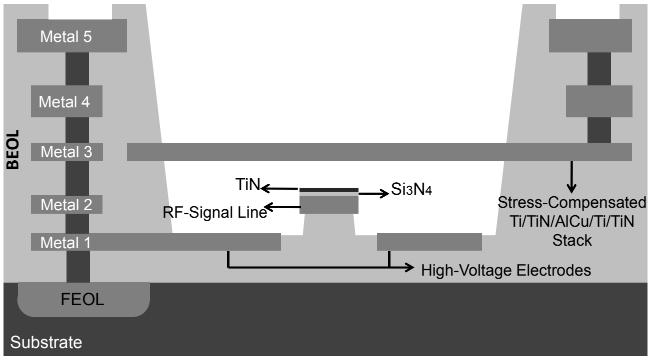

Fig. 1 Cross section of the embedded RF-MEMS switch.

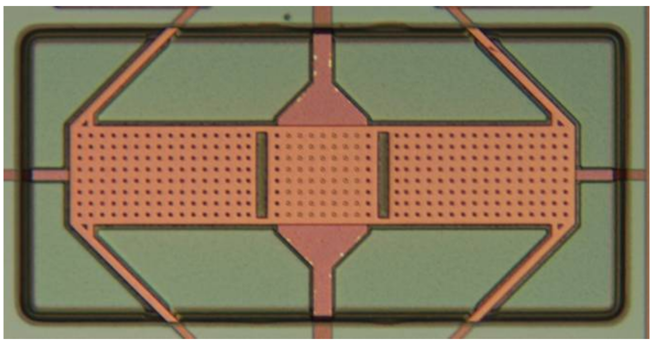

Fig. 2 Die photo of the RF-MEMS switch.

III. MODELING

The mechanical and RF performance of the RF-MEMS switch have been analyzed. The geometry and the process parameters were optimized to achieve the desired S-parameter response with a stable mechanical structure.

A. Mechanical Modeling

CoventorWare® FEM software was used to perform the mechanical analyses of the RF-MEMS switch. The simulations were performed to optimize the geometry and the pull-in voltage. The membrane was modeled as the actual 5-layer stack (Ti/TiN/AlCu/Ti/TiN). From the simulations, it is observed that the membrane stress gradient is mainly defined by the thin Ti-TiN stack, as declared in [12]. The material properties which are required for simulation were taken from the process parameters for each layer. The pull-in voltage of the switch was designed to be below 20V so that this voltage can be generated by electronics available from the BiCMOS process. First, the residual stress values of the membrane layers which have been extracted from measurement results were supplied to the simulator and initially stressed form of the membrane was formed. This step was optimized by observing the fabricated membranes using white-light interferometer as seen in Fig. 3. The measured height difference between M2 and the top of M3 was 2.4µm which is approximately 0.5µm higher than expected (Fig. 3).

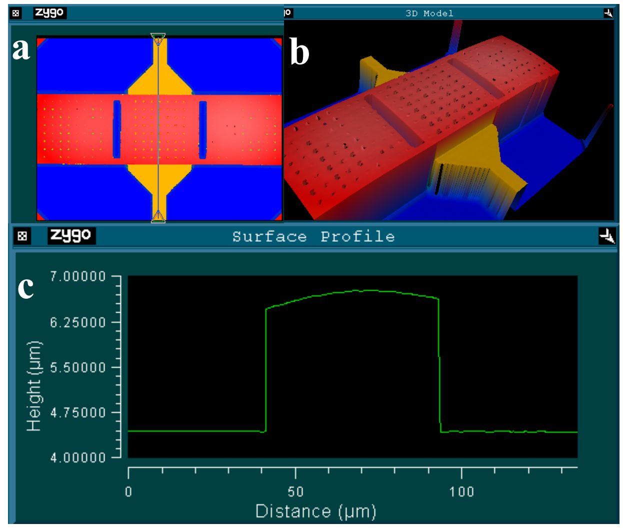

Fig. 3 White-Light Interferometer measurement results: The graph on c shows the height over the line which is indicated in a.

Fig. 4 shows the simulated initial form of the membrane after back and forth optimizations. As obtained from the figure, the height of the membrane increased 0.46µm while the sides decreased 0.78µm. The initially stressed result of the membrane was used as an initial condition of the mechanical simulations. The simulation results for 8V, 12V, 16V and 20V are given in Fig. 5. The pull-in occurred between 16V and 20V as seen from same figure. It is also observed from the simulations that up to 50V electrode voltage, there was no contact between M3 and M1 which would create electrical short between high voltage and ground. The capacitance change between the membrane and signal line (M2) with different electrode voltages is given in Fig. 6. The capacitance of the contact region changed from 40fF to 350fF. The down-state capacitance was lower than the expected due to the stressed form of the membrane. The same effect was also observed from the measurements.

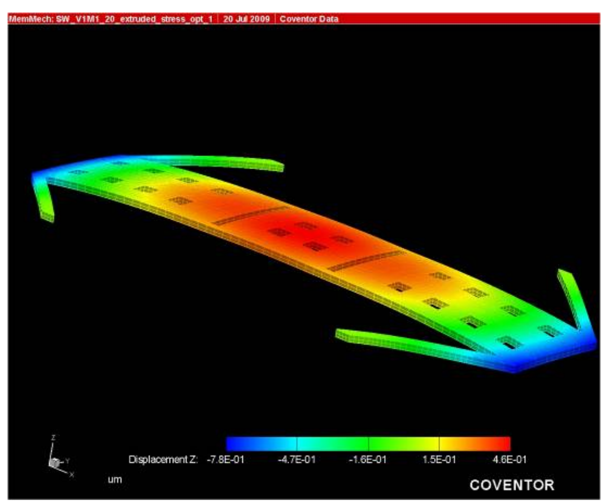

Fig. 4 The simulation result of initially stressed membrane.

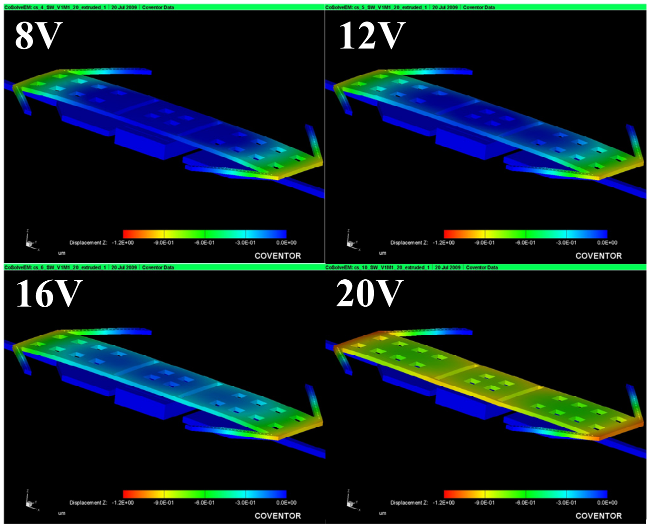

Fig. 5 The simulation results of the switch for 8V, 12V, 16V and 20V electrode voltage.

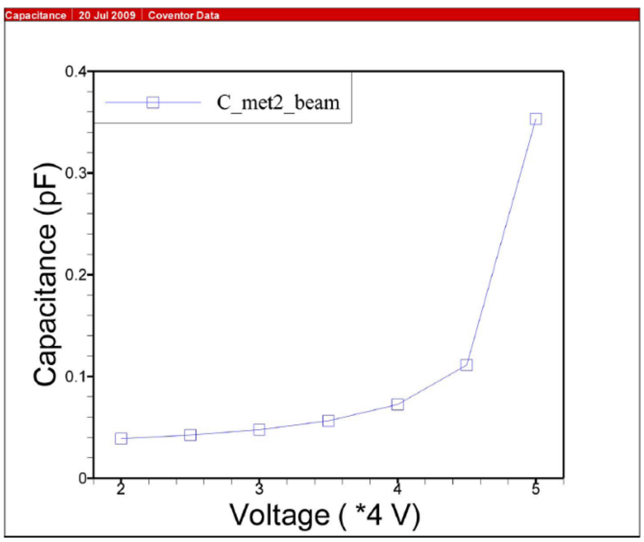

Fig. 6 The simulated capacitance curve of the contact region for different electrode voltages, from 8V to 20V.

B. RF Modeling

The EM simulations of the RF-MEMS switch were performed using Agilent® MOMENTUM tool to analyze the high frequency behavior. The substrate file was defined with respect to IHP's 0.25µm BiCMOS process flow. RF characteristics of the signal line and the membrane of the switch were solved using the Momentum tool while the contact region was added as an RLC circuit model (Fig. 7). The contact regions' RLC component values were extracted from measurement results of the switch by de-embedding the probe-pad and RF-Line parasitic components using Agilent® 4294A Precision Impedance Analyzer.

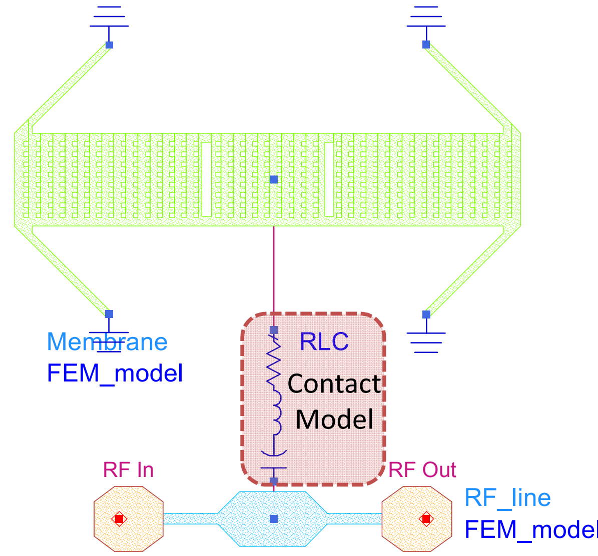

Fig. 7 Complete simulation setup of RF-MEMS switch: RF characteristics of the signal line and the membrane were solved by FEM and the contact RLC model was added.

To measure the scattering parameters from 1GHz to 110GHz an 8510XF network analyzer (NWA) from Agilent® was used. A SOLT calibration on a separate impedance standard substrate was performed. The measured and the simulated S-parameters of the switch are given in Fig. 8 for both "up" and "down" states. As seen from the same figure, the results of the developed model are in a very good agreement with the measured results up to 110GHz. The created compact model is very useful for system simulations including IC components and MEMS switches for RF characterization up to mm-wave frequencies.

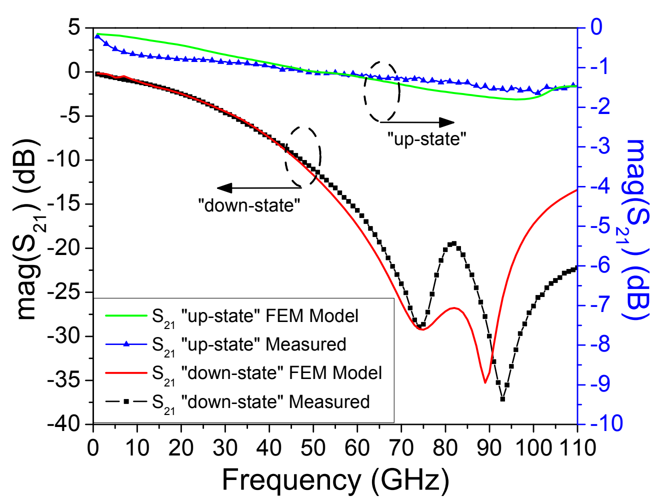

Fig. 8 The measured and the simulated S-parameter results of the switch for both "up" and "down" cases.

IV. DESIGN EXAMPLE

As a proof of concept, a T/R switch was designed and fabricated using the developed RF model of the RF-MEMS switch. The die photography of the T/R switch is given in Fig. 9. For the transmit case, Switch1 is “up” and Switch2 is “down” state, which creates a λ/2 transmission line between port1 and port2. The receive case operates vice versa. The T/R switch was designed for 60 - 70 GHz applications. The insertion loss was measured as below 5 dB and isolation between transmit and receive path was measured as higher than 20 dB for interested frequency band (Fig. 10). The results proved not only the feasibility of using the RFMEMS switches for T/R antenna switches, but also possibility for BiCMOS integrated phase-shifters, reconfigurable circuits and multiband matching networks at mm-wave frequencies.

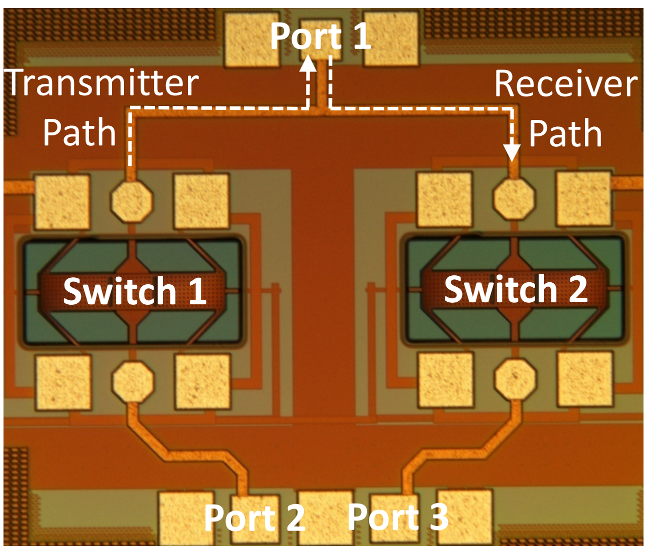

Fig. 9 Die photo of fabricated T/R switch.

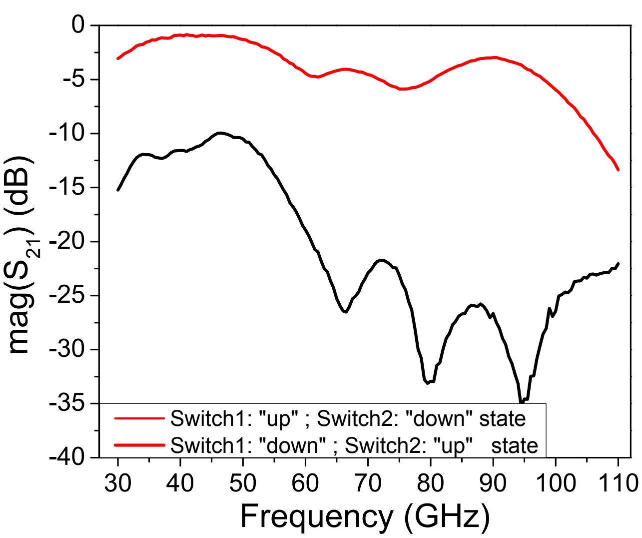

Fig. 10 S-parameter result of the T/R switch for both transmit and receive modes.

V. CONCLUSION

A BiCMOS embedded RF-MEMS capacitive switch for mm-wave integrated circuits has been successfully characterized using Finite-Element-Method (FEM). The residual stress of the thin film membrane was taken into account and used as an initial condition of the mechanical simulations. The S-parameter data was extracted using an EM solver and compared with measured results of the switch up to 110GHz. The simulated capacitance value from mechanical simulations and the extracted S-parameter data from EM simulations showed good agreement with measurement results. The developed model was applied to a T/R antenna switch design. The study proved the feasibility of using the FEM model in circuit simulations for the development of RF-MEMS switch integrated, single-chip multi-band RFICs.

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